

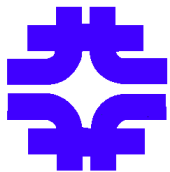
Superconducting Magnet R&D

J. Strait, Fermilab

Fermilab Long Range Planning Committee
open session on Accelerator R&D

18 November 2003

*Thanks to G.Ambrosio, P.Bauer, R.Kephart, J.Kerby,
V.V.Kashikhin, A.V.Zlobin (FNAL);
A.Devred (Saclay/CERN); S.Gourlay, G.L.Sabbi (LBNL);
M.Harrison (BNL); A.Yamamoto (KEK)
for use of their viewgraphs.*



Why Superconducting Magnet R&D??

Superconducting magnets are an *enabling technology* for present and future accelerators for Fermilab and High Energy Physics:

- Tevatron
- LHC and LHC upgrade
- VLHC
- Muon collider / neutrino factory
- Superconducting linear collider

An intellectually active superconducting magnet group supports current and future Tevatron programs:

- Studies of Tevatron magnet behavior to improve Tevatron performance (e.g. "snap-back," alignment, etc.)
- Magnets for new CO IR for BTeV.
- Possible higher field Tevatron dipoles to make space for new equipment (e.g. more separators, instrumentation, etc.)



Magnet R&D: Tevatron

Tevatron is 20 yrs old why are you doing magnet R&D ?

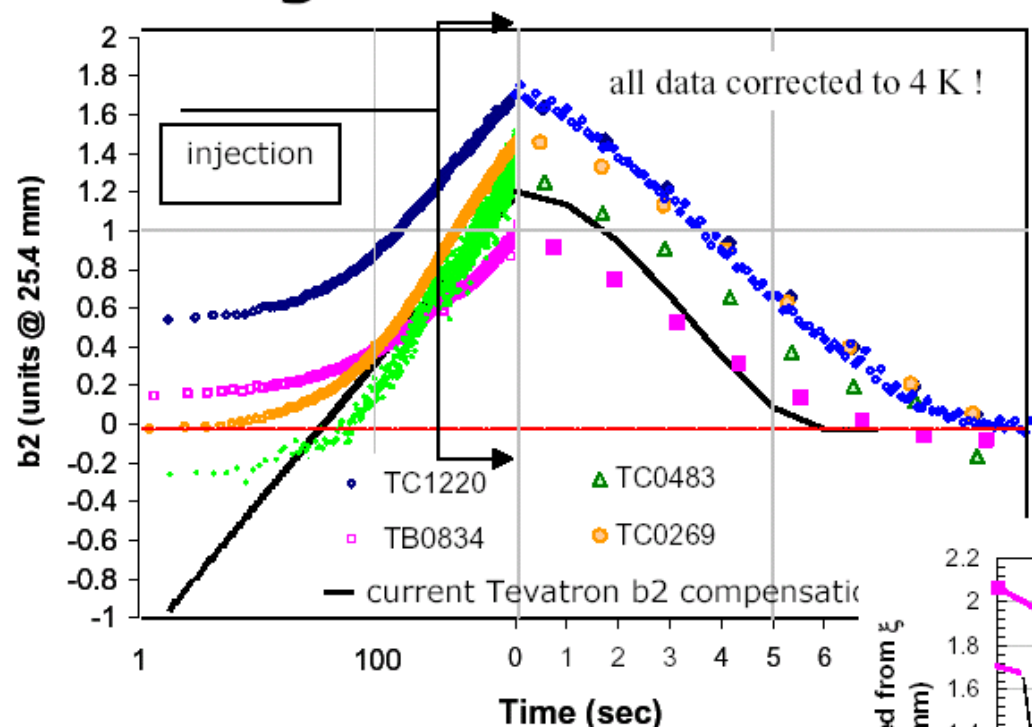
❖ **Long range beam-beam interactions in the Tevatron Collider require helical orbits with large separation.**

- **This and the larger beam intensities in Run II require careful control of the machine tune to limit emittance growth/losses**
- **→Tevatron is now more sensitive to magnet errors**

❖ **Persistent current effects in the superconducting cable result in multipole contributions with:**

- **non-linear time dependent drifts**
- **non-linear hysteretic effects (e.g. snapback)**
- **dependence on the excitation history of the magnet**
- **variations from magnet to magnet because of construction differences (e.g. superconductor from different vendors)**

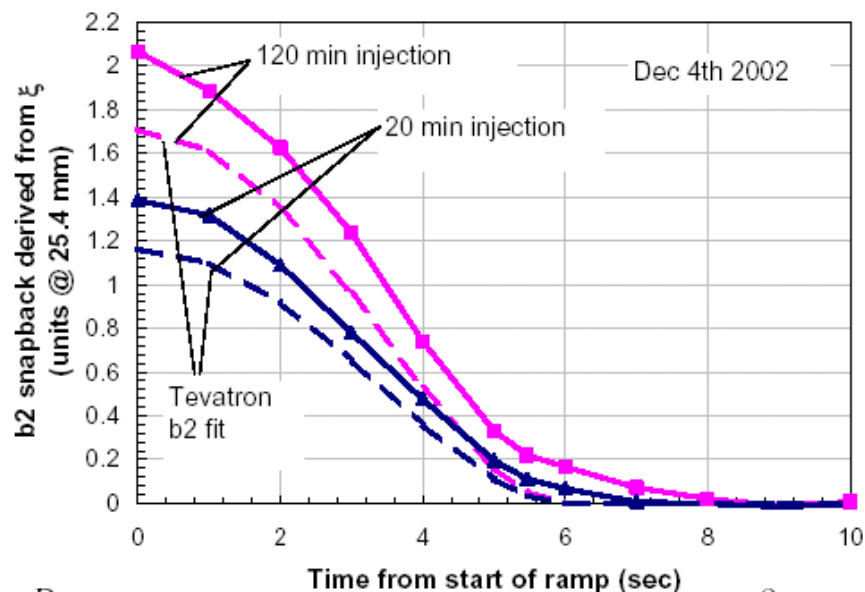
Magnetic measurements – dynamic b2



- time-structure of SB
- drift amplitude
- magnet-to-magnet spread in dynamic effects

Above: b_2 D&SB after 30 min injection porch for a standard pre-cycle in 4 Tevatron dipoles

Right: average Tevatron dipole b_2 SB after 20&120 min IP, derived from measured beam chromaticity.



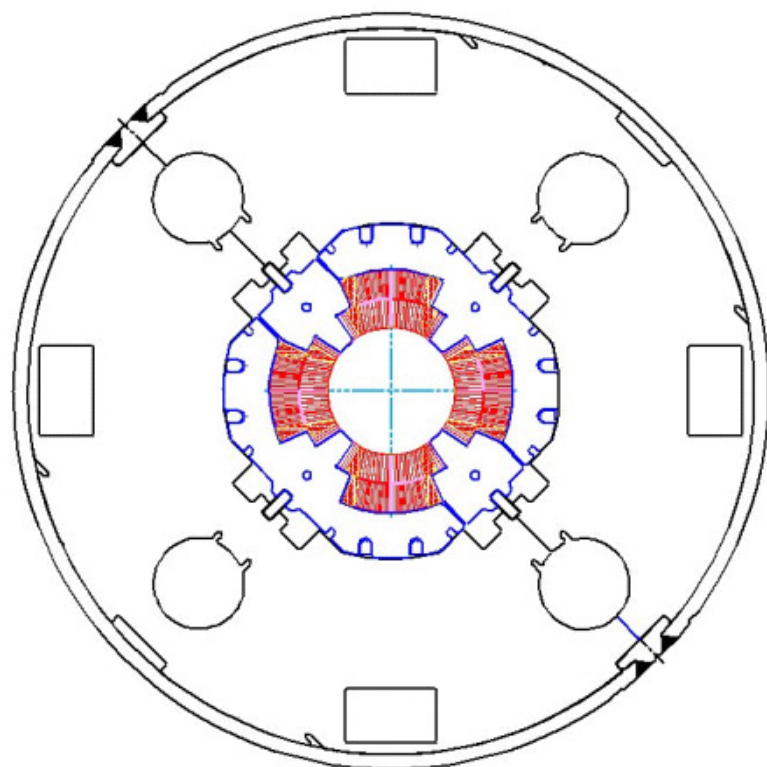
SMPAC June 4th 2003

Pierre Bauer

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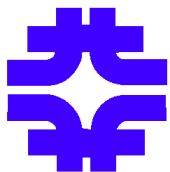


LHC IR Quadrupoles

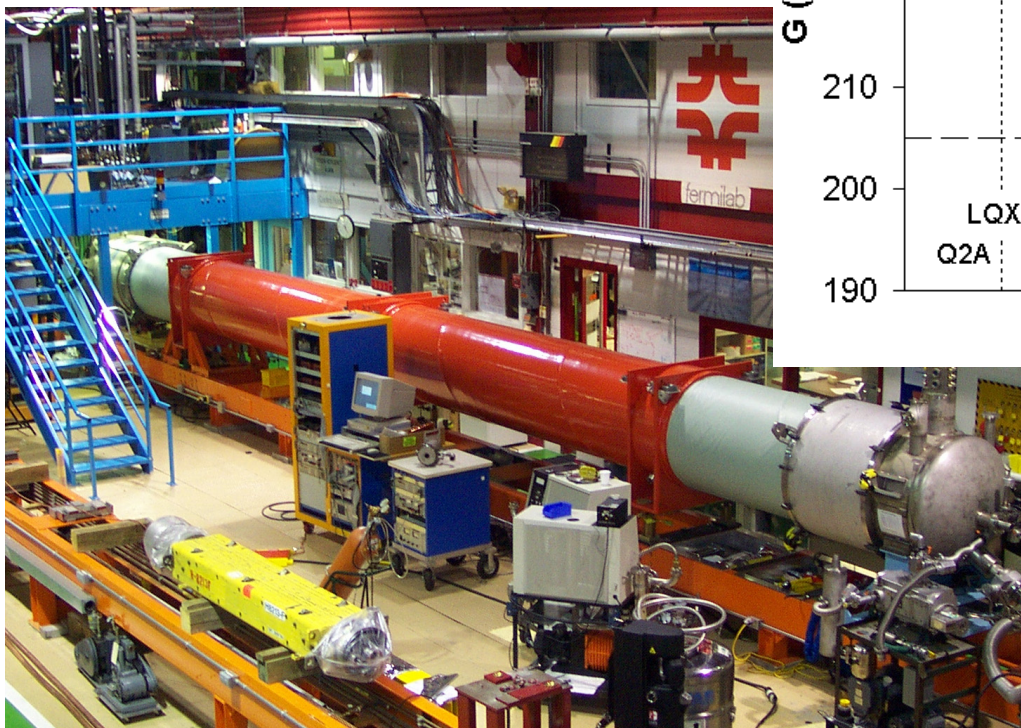
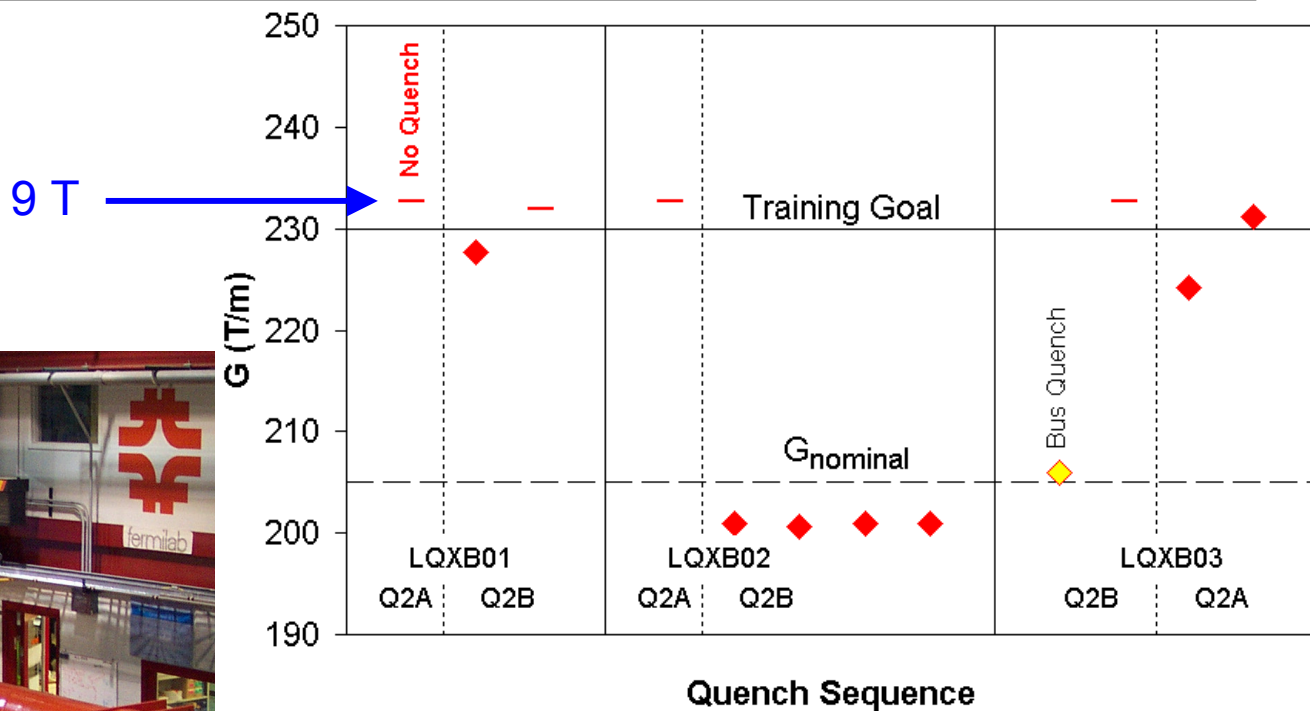


LHC IR Quadrupole Magnet Features

- NbTi Coil; SS collar
- 70mm bore diameter;
- 400mm OD yoke; 416mm OD
- 2K operating temperature
- 205T/m collision gradient
- 215T/m maximum gradient
- 250T/m short sample
- Cryostat designed to accommodate 490mm KEK magnet and external heat exchanger for LHC IR energy deposition



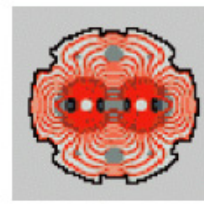
LHC IR Quadrupoles



*The Current State-of-the-Art
... NbTi pushed to the limit.*



Non-Member State Contributions Japan (KEK)



*>14 of 18 IR quads (produced by Toshiba to KEK's design) are done.
Performance matches that of FNAL quads.*



Cross Section



A. Yamamoto

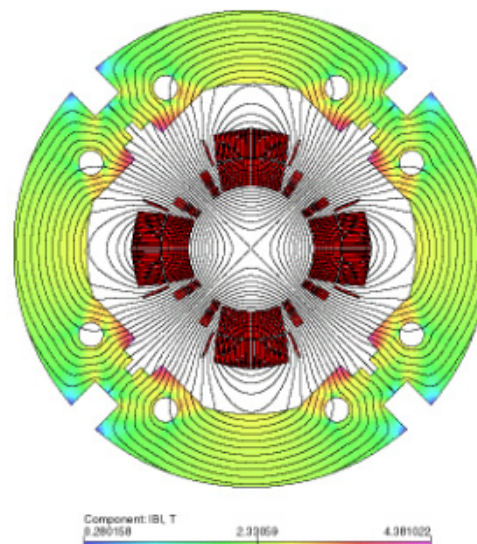
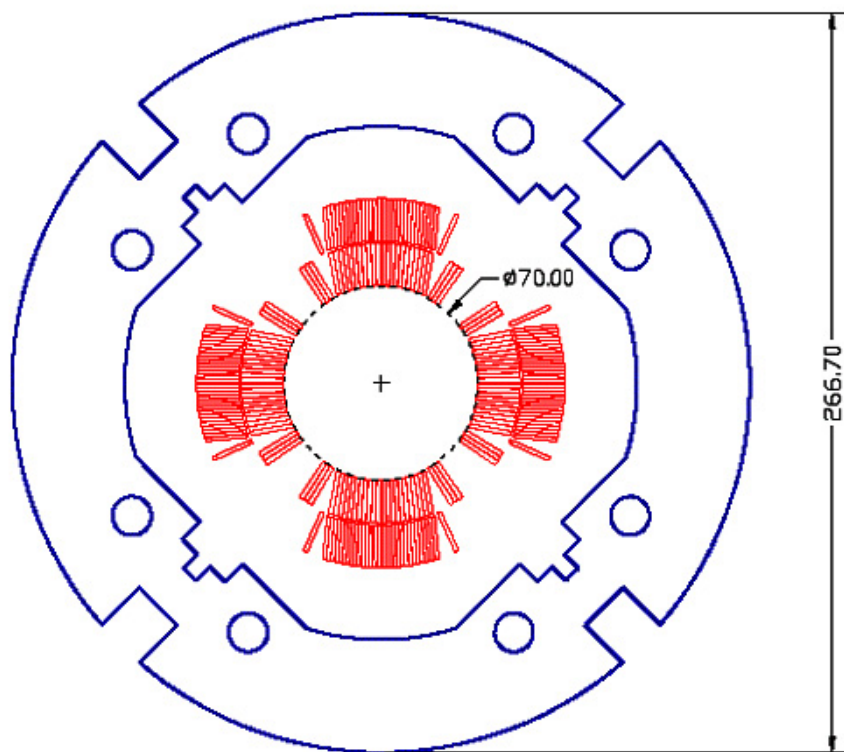
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LHC Spin-off: C0 IR Quads for BTeV

LHC optimized for C0:

- Coil cross section & mechanical support the same
- Operates at 4.5K
- Iron yoke OD reduced $\sim 130\text{mm}$
- Beam Height reduced to $\sim 250\text{mm}$





SC Magnets
at Fermilab

Pushing Beyond the State-of-the-Art

High Field Magnet R&D Program Goals

HFM Program is focused on the development of next generation SC accelerator magnets with high operating fields ($>10\text{T}$ at 4.5 K) and high operating margins for different applications.

Program was started in 1998 and driven by VLHC which determined main magnet parameters such as field range, aperture, magnet design, etc.

The program is focusing on practical designs

- **we worry about aperture and length, field quality, protection, manufacturability, cost, reproducibility, etc... not just peak field**

Fermilab AAC,
21 November 2003

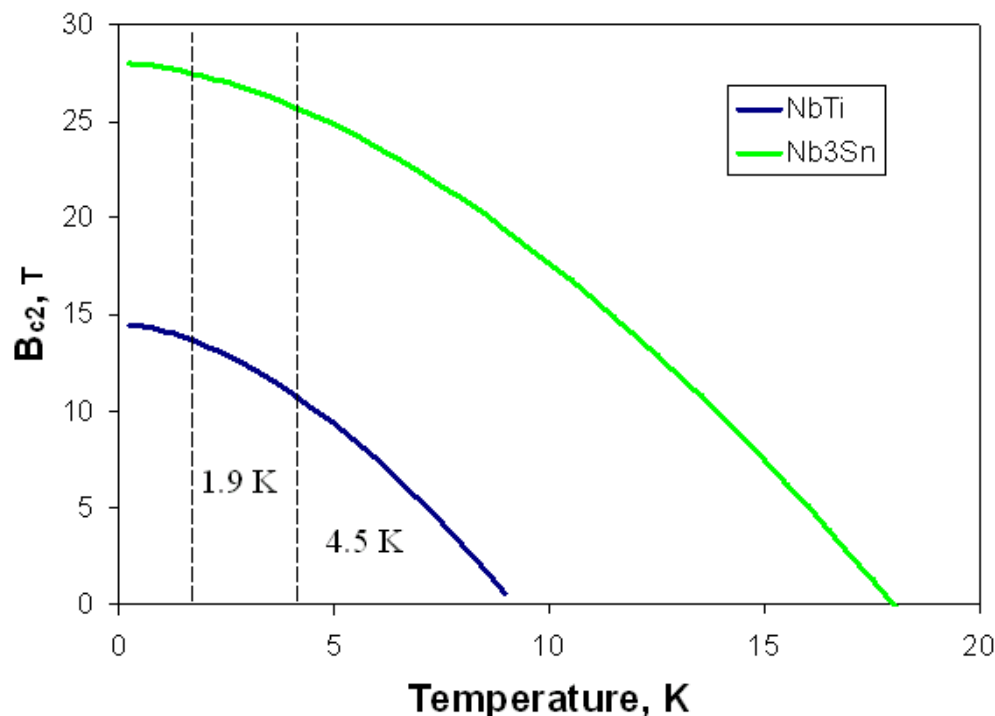
A. Zlobin
High Field Magnet Program

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Why Nb₃Sn ?

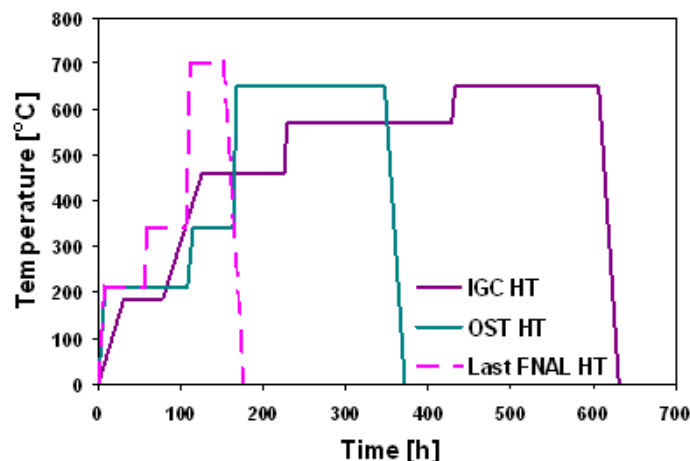
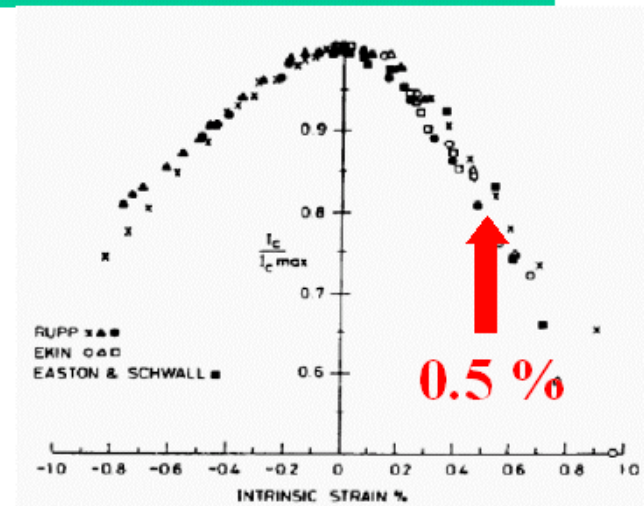
- ❖ Critical field is much higher than NbTi
- ❖ High current density Nb₃Sn conductor is commercially available in long lengths
- ❖ But...very difficult engineering material because it is brittle.





Nb₃Sn Challenges

- ❖ After heat treatment Nb₃Sn conductor is very sensitive to permanent strain degradation of I_c
 - 25% Loss of I_c at 0.5% strain
 - NbTi loses 25% in I_c at 4% strain when it breaks
- ❖ If conductor is heat treated before winding one must carefully control the strain on the conductor for its entire lifetime → large bending radii
- ❖ Heat treatment after the magnet is wound is also an engineering challenge
 - requires high temperatures (> 600 C)
 - long durations
 - special insulation schemes





High Field Magnet Program

These features of Nb₃Sn lead to two approaches:

❖ **Wind-and-React:**

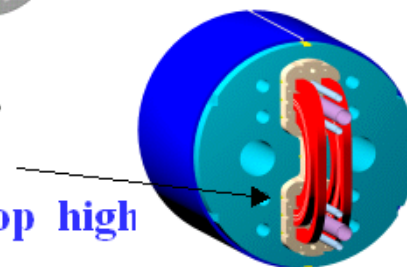
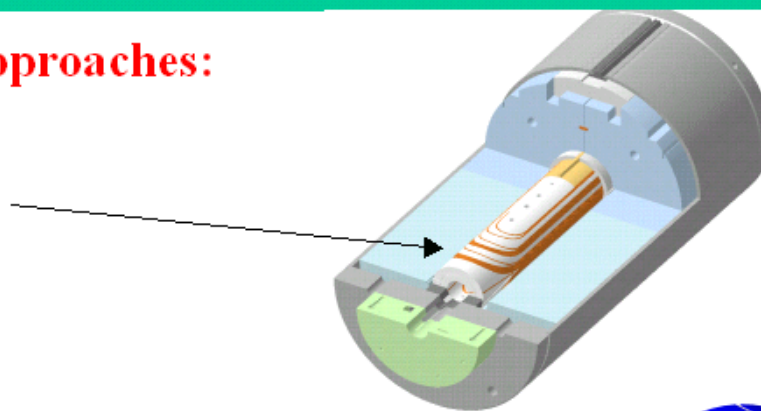
- Familiar $\cos \theta$ shell-type coils
- New high temp insulation schemes
- Carefully engineered strain limits

❖ **React-and-Wind:**

- Large bend radius block-type coils
- Friendly to brittle conductors such as Nb₃Sn and other HTS.
- Arranged in a twin aperture common-coil configuration

❖ **Fermilab is investigating both approaches with the goal to develop high field dipole design suitable for use with Nb₃Sn :**

- Each approach has its challenges \Rightarrow significant development time
- e.g. LHC quad design took 4 yrs but was based on NbTi accelerator magnet development started in early 1970's, Tevatron, HERA, RHIC, etc.
- Practical accelerator magnets based on Nb₃Sn will take a longer



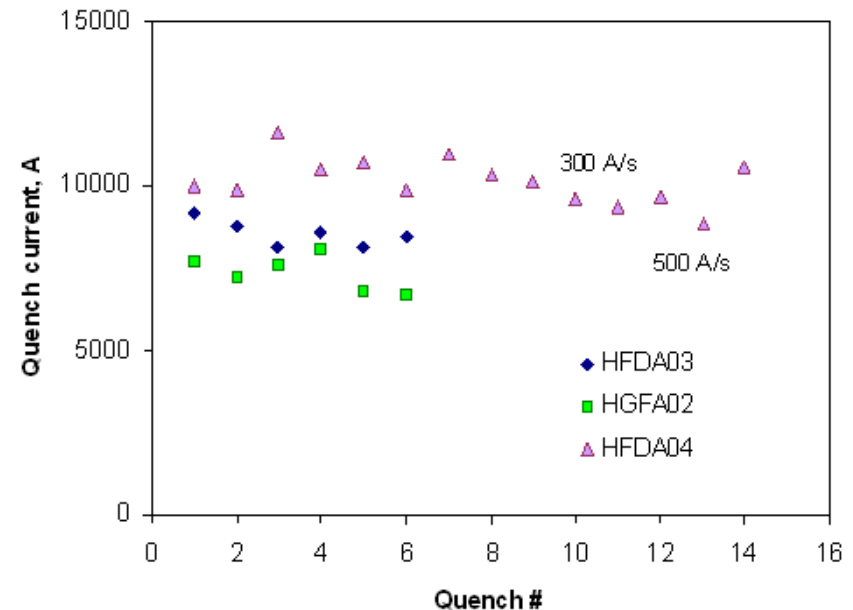


SC Magnets
at Fermilab

Cos-Theta Dipole Test Summary

**Three short models (HFDA02-04)
were fabricated and tested in
FY2001-2002:**

- ❖ **Good, well understood field
quality including
geometrical harmonics and
coil magnetization effects**
 - **We developed and tested a
simple and effective
passive correction system
to correct large coil
magnetization effect in
Nb₃Sn accelerator magnets**
- ❖ **Quench current was only
50-60% of expected short
sample limit (B_{max}~6-7 T)**



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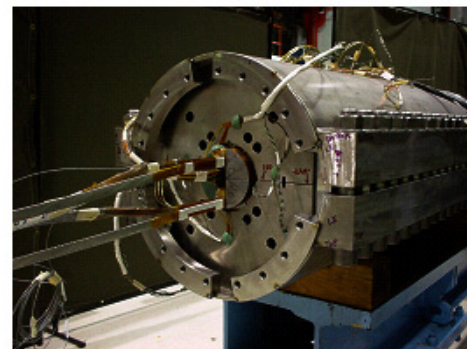
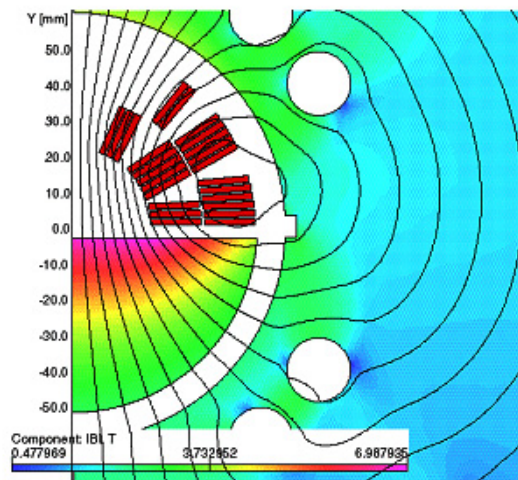
SC Magnets
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Magnetic Mirror

Since last year we focus on understanding and improvement of magnet quench performance.

We study and optimize the W&R technology and quench performance issues using half-coils and a magnetic mirror (HFDM):

- The same mechanical structure and assembly procedure
- Advanced instrumentation
- Short turnaround time, cost effective



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SC Magnets
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W&R, cos-theta technology

We fabricated and tested last year 3 mirror configurations – HFDA03A, HFDA03B and HFDM03. The following causes have been studied:

❖ **Lead splices** (SC transformer, HFDA03A-03B):

- resistance (OK)
- cooling in real conditions (OK, improved)
- BICC (no evidence)

❖ **Insulation and Cable stability** (HFDM02):

- effect of ceramic binder (OK, improved)
- interstrand resistance (OK)

❖ **Technology** (HFDM02):

- tooling (improved old and developed new reaction/impregnation tooling)
- assembly procedures and coil prestress (OK)

❖ **Strand instabilities:**

- we found both by calculations and experimentally large I_c degradation in Nb3Sn strands at low fields
- we observed instabilities in cable and magnets.

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R&W Common Coil Dipole

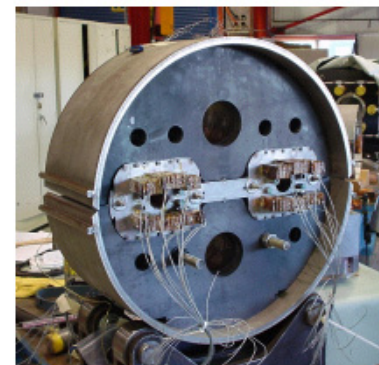
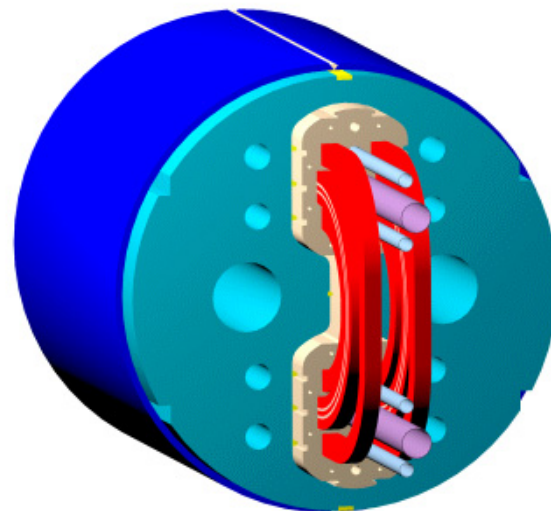
Common coil dipole model (HFDC):

- High-Jc 0.7 mm Nb3Sn strand
- Wide pre-reacted 60-strand cable
- Single-layer coil with cold iron yoke
- Advanced mechanical structure
- Magnet bore of 40 mm
- Nominal field of 11 T at 4.5 K

Mechanical and technological models were fabricated and tested in FY2002.

The 1st common coil short model has been fabricated and tested in FY2003:

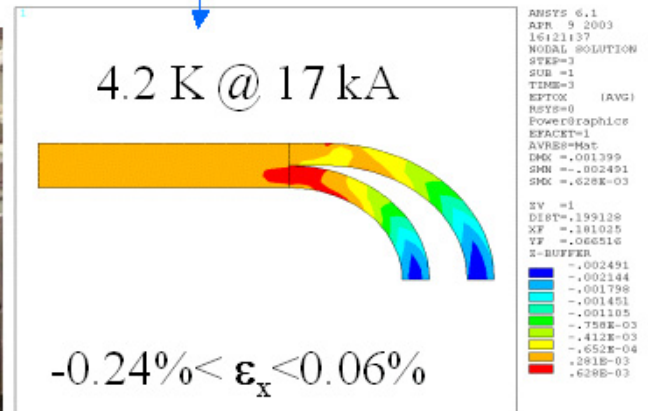
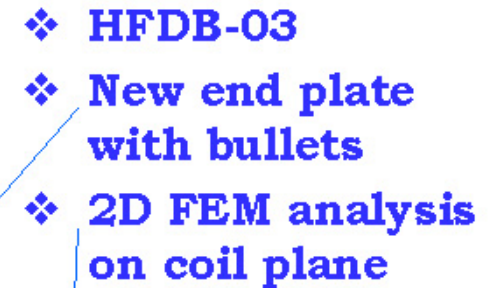
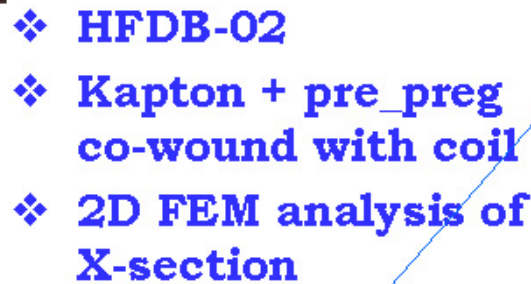
- Good, well understood field quality
- Long training, ~75% of quenches occurred in one of two coils
- Max quench current reached 60% of the short sample limit



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R&W summary

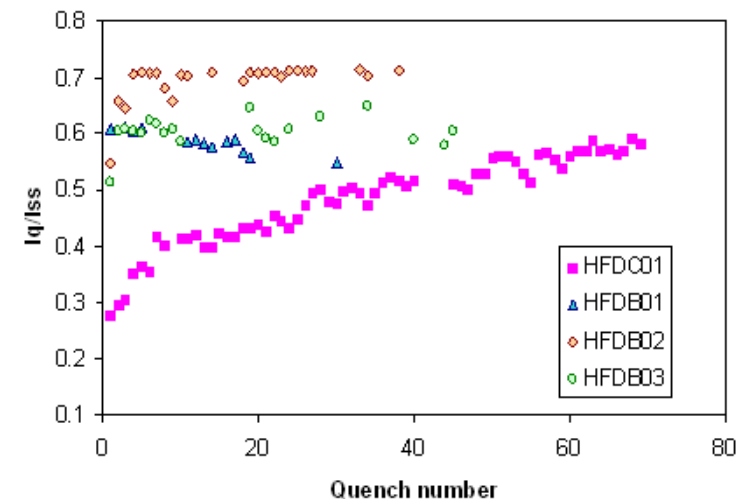
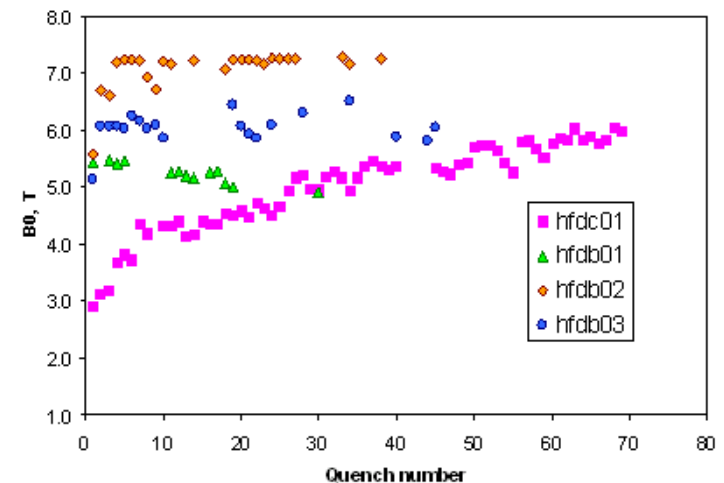
Four 1-m long dipoles based on reacted Nb₃Sn cable were fabricated and tested. All of them survived during complicate fabrication process and reached 60-70% of SSL.

The critical current degradation of reacted cable was much larger than expected due to:

- **Conductor limitations**
- **Magnet mechanics**

To use this technological approach in accelerator magnets both the conductor and the magnet mechanics have to be improved.

We are planning to focus on the conductor studies and improvements.



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Material and Component R&D

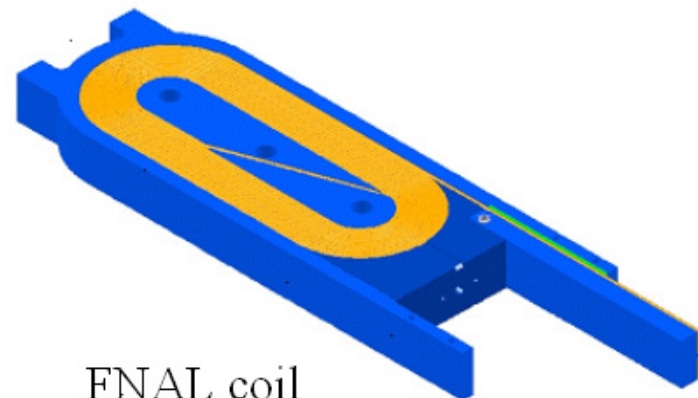
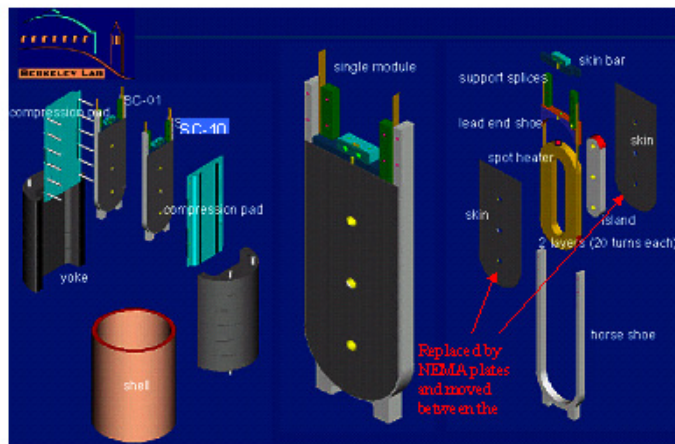
- ❖ **New generation accelerator magnets requires advanced superconductors, structural materials and components.**
- ❖ **Fermilab developed infrastructure to perform extensive material R&D in support of the magnet R&D**
 - **Small ovens for Nb₃Sn strand and cable Heat Treatment**
 - **Compact 28-strand cabling machine**
 - **Sample compression fixtures (4.2-300K)**
 - **I_c and magnetization sample holders**
 - **compact 25 kA SC transformer**
 - **SEM and optical microscopes**
 - **Short Sample Test Facility**
 - **15-17 T solenoid,**
 - **1.5-100 K temperature insert**
- ❖ **Fermilab is participating in national programs sponsored by DOE**





SC Magnets
at Fermilab

Cable Testing Using Small Racetracks



FNAL coil

We plan cable testing using the technique developed at LBNL.

The goals are:

- **Test and optimize real full-size cables before using in magnets**
- **Use well understood mechanical structure to avoid effects related to test setup**
- ❖ **LBNL-type racetrack is being fabricated, tests TBD with LBNL.**
- ❖ **1st (PIT1.0) and 2nd (MJR1.0) Fermilab coils: tests in January.**
- ❖ **3rd (RRP0.7) and 4th (MJR0.7) coils: tests in April.**

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SC Magnets
at Fermilab

FY2004 Goals and Directions

Focus on W&R technology – basic technology for LARP.

❖ W&R, cos-theta technology:

- **understanding and improvement of magnet quench performance, reaching 10-12 T field level in cos-theta dipole models**

❖ R&W technology:

- **continue work on strand/cable level**

❖ SC and material R&D:

- **support magnet R&D (both base and LARP), start cable testing using small racetracks**
- **contribute to national SC R&D**

❖ LARP magnet R&D:

- **IRQ conceptual design studies and technology development**
- **preparation to short model R&D**



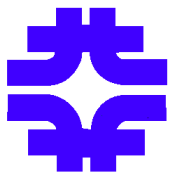
SC Magnets
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Long-term Plan

We are planning production and test of 2-3 short model magnets (including mirrors) per year. The goals are understanding and improvement of the magnet technologies and quench performance, and optimization of the field quality.

When basic problems are understood we plan to increase the production and tests of HFM models of different types (including models for LARP) to 5-6 per year with the goal to study and optimize the performance reproducibility and magnet cost.

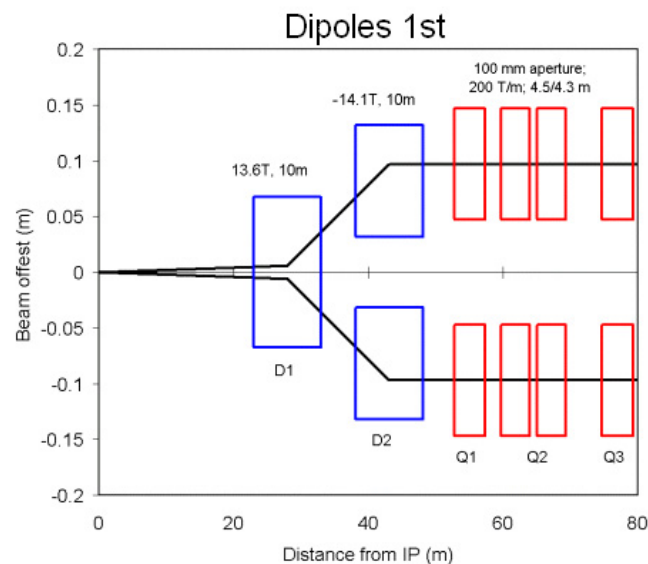
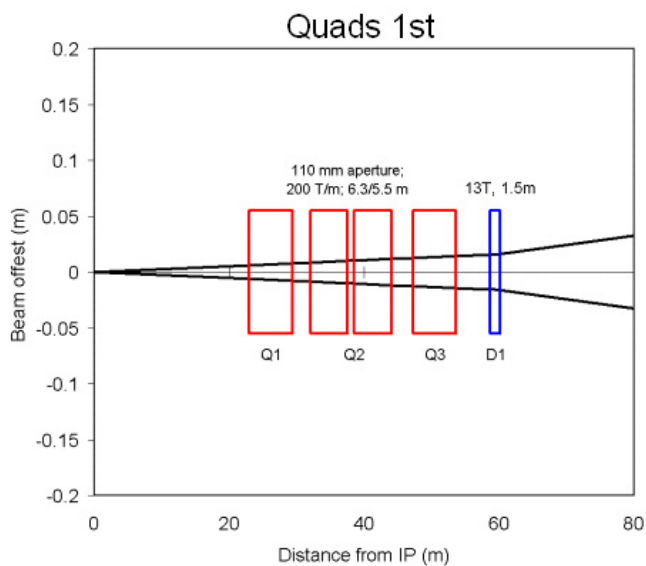
Assuming that short model R&D is successful we could start to develop infrastructure for long models in FY2006-2007 and start test long coils in FY2007.



US LHC Accelerator Research Program: Magnet R&D for LHC Luminosity Upgrade



New IRs: “Straightforward” Designs

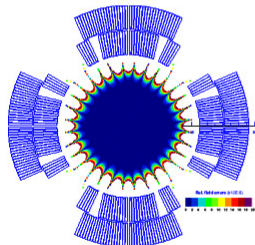


J. Strait, et al., Towards a New LHC Interaction Region Design for a Luminosity Upgrade, PAC 2003.



Quadrupole coil designs

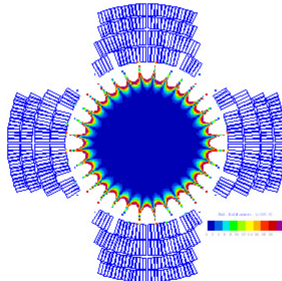
90-mm



$$N_{\text{turns}} = 144$$

$$S_{\text{coil}}, \text{cm}^2 = 48.1$$

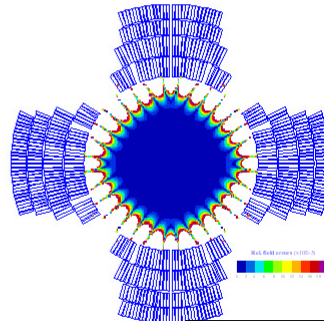
100-mm



$$N_{\text{turns}} = 228$$

$$S_{\text{coil}}, \text{cm}^2 = 59.3$$

110-mm



$$N_{\text{turns}} = 288$$

$$S_{\text{coil}}, \text{cm}^2 = 72.4$$

2003 LARP Collaboration Meeting, September 16-18,
Danfords on the Sound, NY

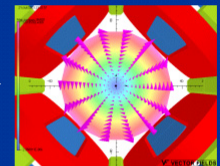
Vadim Kashikhin



Racetrack Quads for the LHC IR?

A) for the ultimate LHC IR application

- (-) Low magnetic efficiency wrt $\cos 2\theta$ /block
- (-) Field quality is more difficult to optimize
- (+) Better if aperture is measured at the midplane →
- (+) Better with nested coils (Gupta, ASC-02)
- (+) Inexpensive fabrication



B) for technology development

- (+) Easily integrates with the SM program and the bladder/key structure
- (+) Cost-effective method to investigate:
 - field quality and related mechanical issues
 - materials, thermal, quench protection studies

BERKELEY LAB

LARP Meeting 9/16-18, 2003

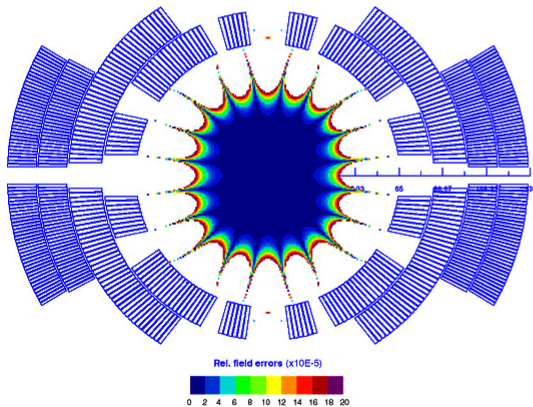
Superconducting Magnet Program

Gian Luca Sabbi

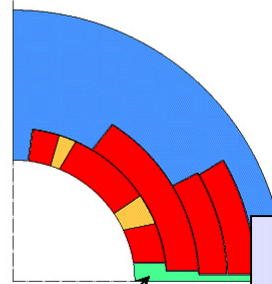


Dipole coil design II

$$D_{\text{bore}} = 130 \text{ mm}, J_c(12\text{T}, 4.2 \text{ K}) = 3000 \text{ A/mm}^2$$



$$\begin{aligned} B_{q_bore} &= 15.8 \text{ T} \\ N_{\text{turns}} &= 282 \\ S_{\text{coil}} &= 119.1 \text{ cm}^2 \end{aligned}$$

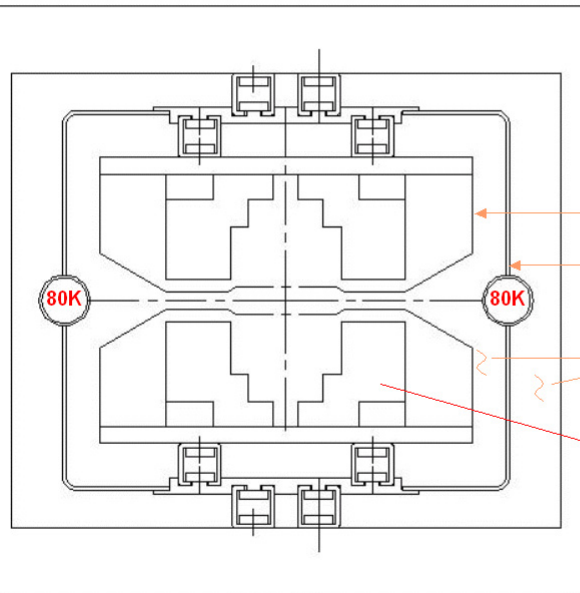


Copper spacer to remove

2003 LARP Collaboration Meeting, September 16-18,
Danfords on the Sound, NY

Vadim Kashukhin

LARP Warm Iron Concept



Dump synchrotron radiations in a relatively warmer structure
(more efficient heat removal)
Cryostat (300K)

Coldmass (4K)**Heat Shield (80K)****Vacuum Space****Superconducting coils****Warm Iron Design**

Superconducting
Magnet Division

BROOKHAVEN
NATIONAL LABORATORY



Program Schedule

Fermilab R&D program on LHC IR upgrade quadrupoles

FY2003-2007 - Conceptual Design Studies

FY2006-2010 – model magnet R&D

We start IRQ model R&D in FY06 with **simplified 1-m long models** (2-layer design) in order to develop basic tooling and infrastructure and start basic technology development.

- **FY2004 – conceptual design of IRQ model**
- **FY2005 – model and tooling design and procurement**

A series of short models will address the issues of magnet **quench performance**, **field quality**, **mechanics**, **quench protection**, **reproducibility**, **long term performance**, etc.

We will start studying **length dependent effects** with 4-m long coils, as soon as we achieve acceptable quench performance.

FY2010-2012 - Model R&D will be followed by the construction of one or more **prototypes** containing all of the **features required for use in the LHC**.

Common-Coil Dipole (Wind and React)

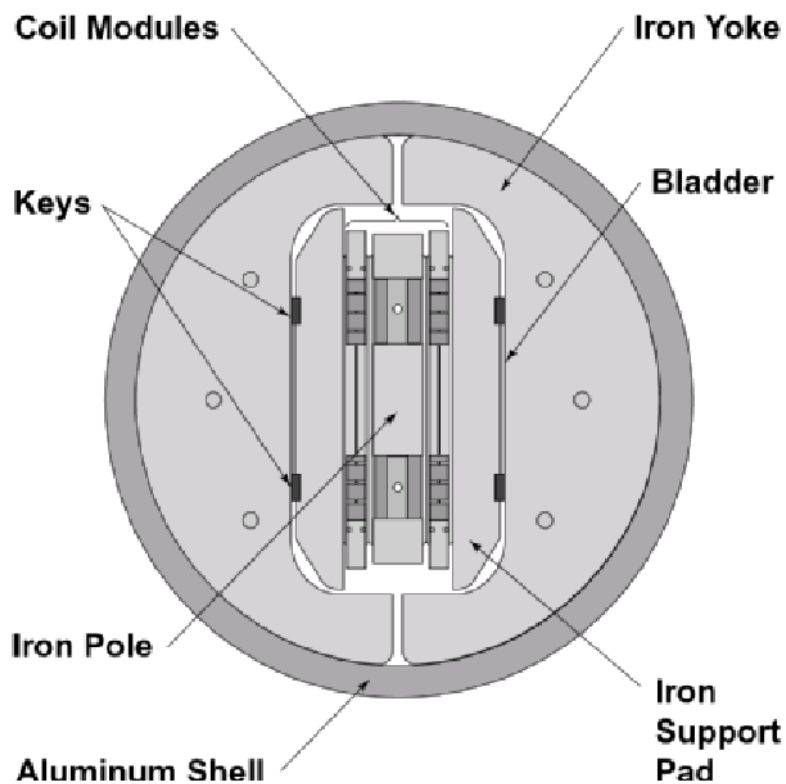


Figure 2. RD-3 Cross Section

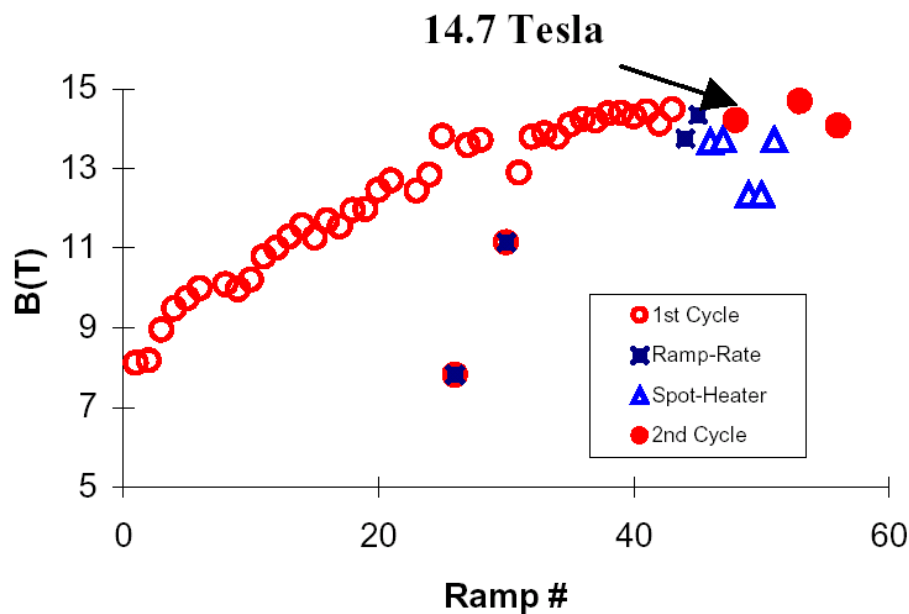
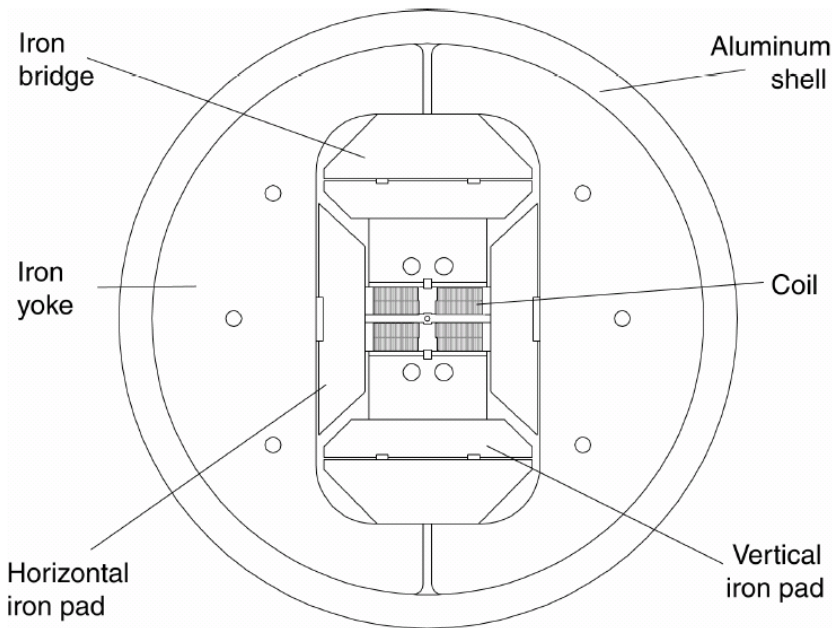


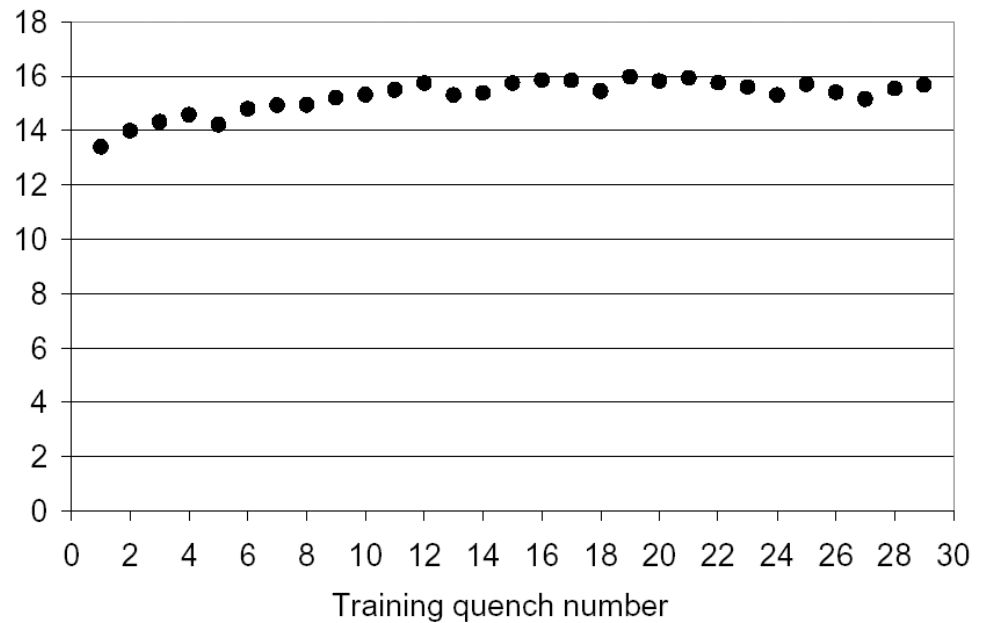
Figure 4: RD-3b Quench History.

Block-Coil Dipole (Wind and React)

Record field (16 T) in a dipole-like geometry



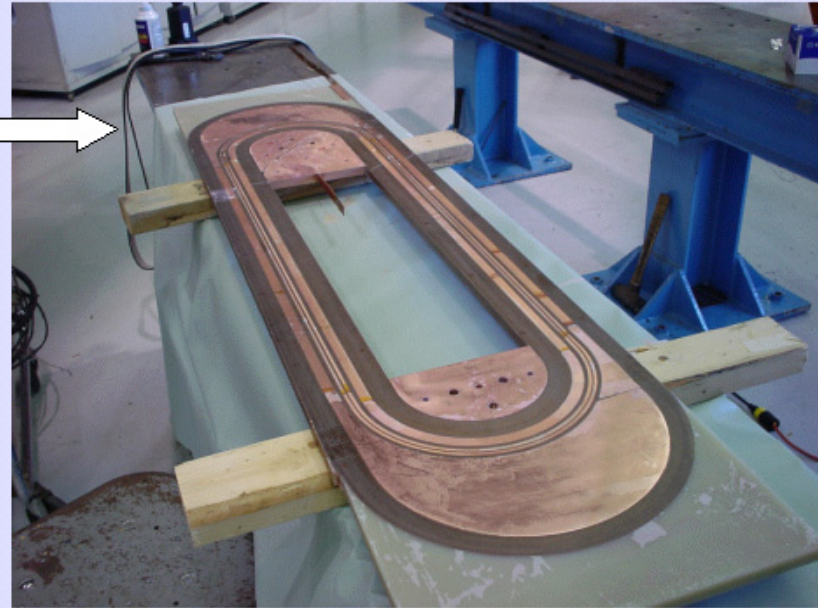
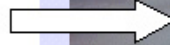
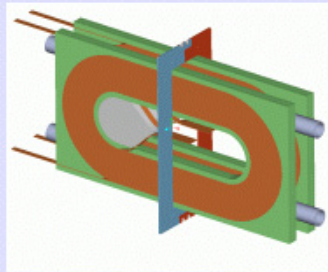
HD1 magnet cross-section. The outer diameter of the shell is 74 cm.



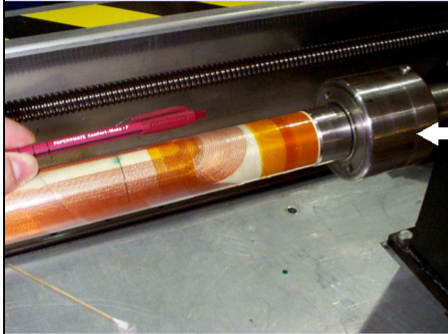
HD-1 training history (first thermal cycle)

BNL Superconducting Magnet Division - High Fields

High Field R&D: Nb₃Sn and HTS flat coil fabrication and testing.



- Goal of a 12 T magnet in FY04
 - Recent Nb₃Sn coils only operate at 70% of short sample (!!)
 - HTS coils continue to improve



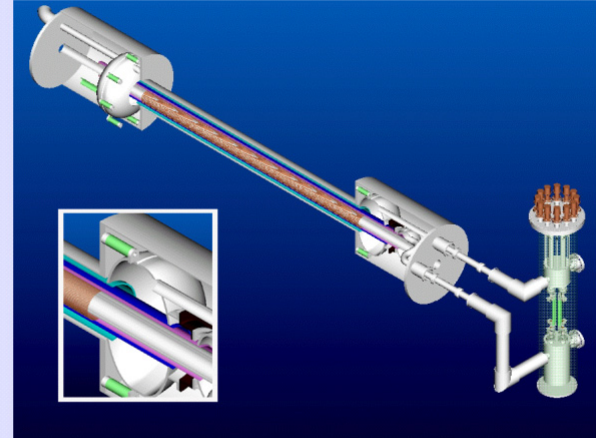
Linear Collider final focus R&D: ultra compact "direct wind" superconducting magnets. Similar technology to HERA/BEPC micro-beta quads

Magnetically not too demanding
Looks like it can be built
Vibration tolerances at the 1nm level !

Superconducting
Magnet Division



RHIC II - E-Cooling Solenoid Conceptual design



- Working on the end configuration which would include short (phase advance) quadrupoles

Superconducting
Magnet Division



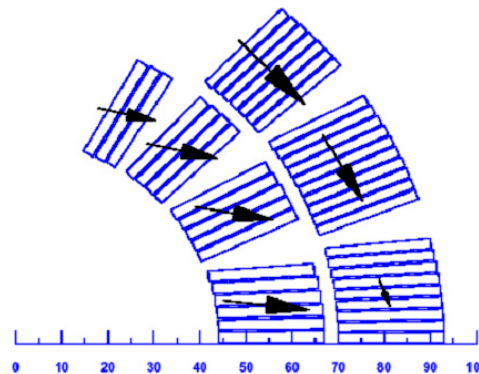
Next European Dipole (NED) Joint Research Activity

presented by A. Devred (CEA/DSM/DAPNIA and CERN/AT)

on behalf of the NED Collaboration
CCLRC/RAL—CEA/DSM/DAPNIA—CERN/AT—INFN/Milano—
LASA & INFN/Genova—Twente University—Wroclaw
University)

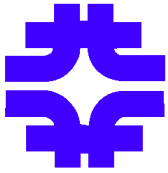
CERN
20 November 2003

NED Preliminary Design (1/2)



Possible $\cos\theta$ conductor distribution
to produce 15 T in a 88-mm aperture
(Courtesy O. Vincent-Viry)

- Preliminary computations have already been carried out at CERN to study the feasibility of a 88-mm aperture, 15-T dipole magnet.
- The selected structure relies on a “conventional,” two-layer, $\cos\theta$ distribution of high-aspect ratio, Rutherford-type cables with graded current densities.



Summary

Superconducting Magnet R&D is and should be a vital part of the Fermilab scientific program.

- Supports on-going the Tevatron program.
- Provides the basis for future accelerators and upgrades to existing ones that will advance HEP.

Active R&D at Fermilab includes:

- Studies of Tevatron magnets.
- LHC IR quad and CO IR quad development and construction.
- High-gradient Nb₃Sn quadrupoles for LHC luminosity upgrade.
- High-field dipoles for future hadron colliders.

Superconducting Magnet R&D is part of a world-wide effort:

- Other US Labs
- European Labs
- Japan